

# Observation of a narrow baryonic state in DIS at HERA

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A resonance search has been made in the  $K_S^0 p$ ,  $K_S^0 \bar{p}$  and  $K^+ p$  invariant-mass spectra measured with the ZEUS detector at HERA using an integrated luminosity of  $121 \text{ pb}^{-1}$ . The search was performed in the central rapidity region of inclusive deep inelastic scattering at an  $ep$  centre-of-mass energy of 300–318 GeV for exchanged photon virtuality,  $Q^2$ , above  $1 \text{ GeV}^2$ . The results support the existence of a narrow state in  $K_S^0 p$  and  $K_S^0 \bar{p}$  decay channels, consistent with the pentaquark prediction. No signal was found in the  $K^+ p$  decay channel.

## I. INTRODUCTION

Recent results from fixed-target experiments triggered new interest in baryon spectroscopy after observing a narrow baryonic resonance in the  $K^+ n$  decay channel with a mass of approximately 1530 MeV and positive strangeness [1, 2, 3, 4]. Such a state can be interpreted as a bound state of five quarks, i.e. as a pentaquark,  $\Theta^+ = uud\bar{s}$ . According to the predictions of the chiral soliton model [5],  $K_S^0 p$  and  $K_S^0 \bar{p}$  (denoted as  $K_S^0 p(\bar{p})$ ) decays are also possible. For the  $K_S^0 p$  channel, evidence for a corresponding signal has been seen by other low-energy fixed-target experiments [6, 7, 8, 9, 10]. Recently, two other pentaquark candidates have also been reported [11, 12].

The  $K_S^0 p(\bar{p})$  decay channel is expected for the PDG  $\Sigma$  bumps [13], which have been observed by early fixed-target experiments. Such unestablished resonances are too low in mass to be accommodated in most quark models. The presence of such states in the mass regions close to the production threshold of  $K_S^0 p(\bar{p})$  final state complicates the search for possible pentaquark.

The  $\Theta^+$  state and the  $\Sigma$  bumps discussed above have never been observed in high-energy experiments, where hadron production is dominated by fragmentation.

This paper discusses recent ZEUS results [14] on the search for exotic baryons in the  $K_S^0 p(\bar{p})$ ,  $K^+ p$ ,  $K^- \bar{p}$  invariant-mass spectra measured with the ZEUS detector at HERA. The measurements were based on the central pseudorapidity region ( $|\eta| \leq 1.5$ ) where the contribution from the fragmentation of the proton remnant is negligible. If the pentaquark state is produced without the net baryon number carried by the proton remnant, emerging from the emissions of gluons and quarks in the hadronisation process, this would open a new chapter in our understanding of non-perturbative QCD.

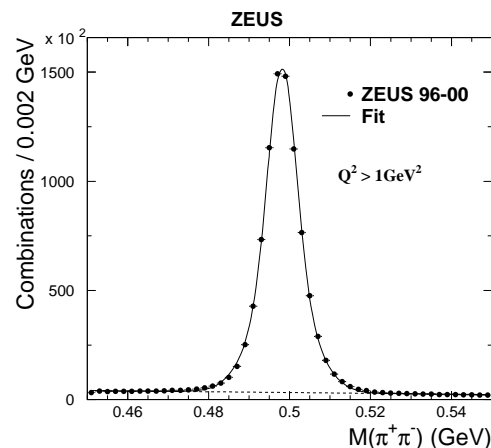


FIG. 1: The  $\pi^+\pi^-$  invariant-mass distribution for  $Q^2 > 1 \text{ GeV}^2$ . The solid line shows the fit result using two Gaussians plus a linear background, while the dashed line shows the linear background.

## II. EVIDENCE FOR A BARYONIC STATE DECAYING TO $K_S^0 p(\bar{p})$

The present analysis was performed using deep inelastic scattering events measured with exchanged-photon virtuality  $Q^2 \geq 1 \text{ GeV}^2$ . The data sample corresponds to an integrated luminosity of  $121 \text{ pb}^{-1}$ , taken between 1996 and 2000. The analysis is based on charged tracks measured in the central tracking (CTD). The tracks were selected with  $p_T \geq 0.15 \text{ GeV}$  and  $|\eta| \leq 1.75$ , restricting this study to a region where the CTD track acceptance and resolution are high.

$K_S^0$ -mesons were identified by their charged-decay mode,  $K_S^0 \rightarrow \pi^+\pi^-$  (see Fig. 1). The candidates with  $p_T(K_S^0) > 0.3 \text{ GeV}$  and  $|\eta(K_S^0)| < 1.5$  were retained. To eliminate contamination from  $\Lambda(\bar{\Lambda})$  decays, candidates with a proton mass hypothesis  $M(p\pi) < 1121 \text{ MeV}$  were rejected.

The (anti)proton-candidate selection used the energy-loss measurement in the CTD,  $dE/dx$ . As example, Fig. 2 shows the  $dE/dx$  distribution as a function of the track momentum for negative tracks. Clear antiproton

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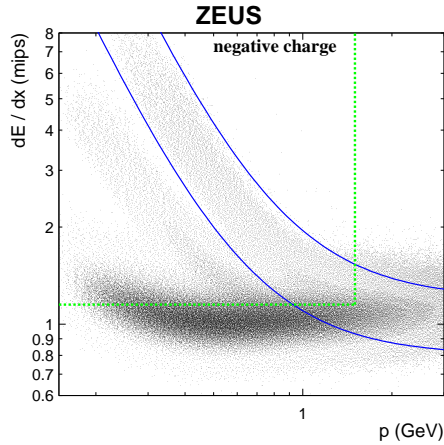


FIG. 2: The  $dE/dx$  distribution as a function of the track momentum,  $p$ , for negative tracks. The solid lines indicate the antiproton band used in this analysis, while the dotted lines indicate the selection cuts  $dE/dx > 1.15$  mips and  $p < 1.5$  GeV used in the  $K_S^0 p(\bar{p})$  reconstruction.

and  $K^-$ -meson bands were observed ( $dE/dx$  for Monte Carlo simulations and for positive tracks have similar qualities, not shown).

$K_S^0 p(\bar{p})$  invariant masses were obtained by combining  $K_S^0$  candidates in the mass region 480 – 510 MeV with (anti)proton candidates in the (anti)proton  $dE/dx$  band with the additional requirements  $p < 1.5$  GeV and  $dE/dx > 1.15$  mips in order to reduce the pion background. The CTD resolution for the  $K_S^0 p(\bar{p})$  invariant-mass near 1530 MeV, estimated using Monte Carlo simulations, was  $2.0 \pm 0.5$  MeV for both the  $K_S^0 p$  and the  $K_S^0 \bar{p}$  channels.

Figure 3 shows the  $K_S^0 p(\bar{p})$  invariant mass for  $Q^2 > 20$  GeV<sup>2</sup>, as well as for the  $K_S^0 p$  and  $K_S^0 \bar{p}$  samples separately (shown as inset). The distribution of the ARIADNE Monte Carlo model was normalised to the data in the mass region above 1650 MeV. The data are above the Monte Carlo prediction near 1470 MeV and 1522 MeV, with a clear peak at 1522 MeV.

To extract the signal seen at 1522 MeV, the fit was performed using a background function plus two Gaussians. The background has the threshold form  $F(M) = P_1(M - m_K - m_p)^{P_2}(1 + P_3(M - m_K - m_p))$ , where  $m_K$  and  $m_p$  are the masses of the kaon and the proton, respectively, and  $P_{i=1,2,3}$  are free parameters. The first Gaussian, which significantly improves the fit at low masses, may correspond to the unestablished PDG  $\Sigma(1480)$ . The second Gaussian describes a pronounced peak at 1522 MeV. The peak position determined from the fit was  $1521.5 \pm 1.5(\text{stat.})_{-1.7}^{+2.8}(\text{syst.})$  MeV. It agrees well with the measurements by HERMES, SVD and COSY-TOF for the same decay channel [7, 8, 9]. The measured Gaussian width of  $6.1 \pm 1.6(\text{stat.})_{-1.4}^{+2.0}(\text{syst.})$  MeV was above, but rather close to the experimental resolution.

In order to determine the natural width of the pos-

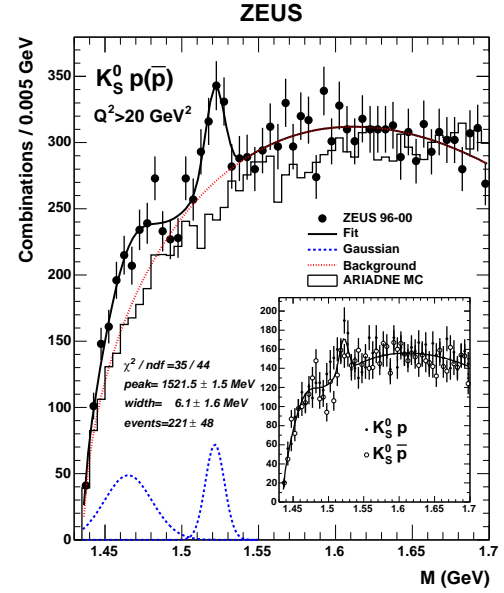


FIG. 3: Invariant-mass spectrum for the  $K_S^0 p(\bar{p})$  channel for  $Q^2 > 20$  GeV<sup>2</sup>. The solid line is the result of a fit to the data using the threshold background plus two Gaussians. The dashed lines show the Gaussian components, while the dotted line indicates background. The prediction of the ARIADNE simulation is normalised to the data in the mass region above 1650 MeV. The inset shows the  $K_S^0 p$  (open circles) and the  $K_S^0 \bar{p}$  (black dots) candidates separately, compared to the result of the fit to the combined sample scaled by a factor of 0.5.

Fit function	peak	width	events	$\chi^2/\text{ndf}$
Bkg.	-	-	-	69/50
Gaussian+Bkg.	$1522.2 \pm 1.5$	$4.9 \pm 1.3$	$155 \pm 40$	51/47
2 Gaussians+Bkg.	$1521.5 \pm 1.5$	$6.1 \pm 1.6$	$221 \pm 48$	35/44

TABLE I: Fit results (in MeV) for  $Q^2 > 20$  GeV<sup>2</sup>. All parameters are free in the fitting procedure.

sible state, the Breit-Wigner function convoluted with the Gaussian was used in the fitting procedure. If the width of the Gaussian is fixed to the experimental resolution, the estimated intrinsic width of the signal was  $\Gamma = 8 \pm 4(\text{stat.})$  MeV. The systematical error on this width is expected to be smaller than the statistical error, but due to low statistics, complicated background and the narrowness of the peak leading to unstable fits, full systematical uncertainty was difficult to estimate.

The number of events ascribed to the signal by this fit was  $221 \pm 48$ . The statistical significance, estimated from the number of events assigned to the signal by the fit, was  $4.6\sigma$ . Other fit parameters are shown in Table 1. The number of events in the  $K_S^0 \bar{p}$  channel was  $96 \pm 34$ . If the signal corresponds to the pentaquark, this provides the first evidence for its antiparticle.

Under a conservative assumption, one could assume that the enhancement from the left side of the 1522 MeV

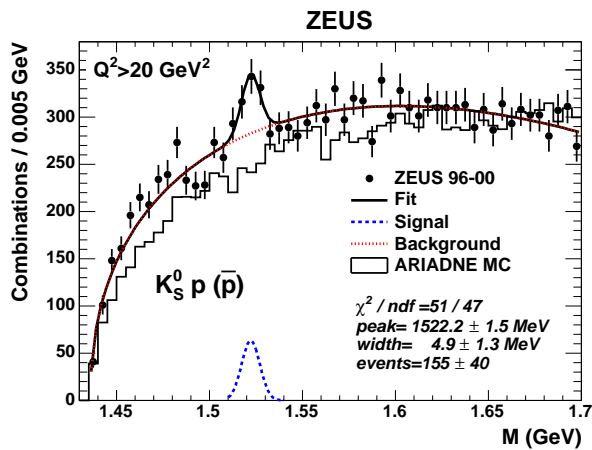


FIG. 4: Same data as in Fig. 3, but fit is performed using a single Gaussian plus the background. The  $\chi^2/\text{ndf}$  is acceptable since it is dominated by the region  $> 1550$  MeV. For  $M < 1550$  MeV, the  $\chi^2/\text{point}$  is 32/22 for the same fit.

peak has a statistical nature, or is due to an instrumental effect which is not taken into account in the Monte Carlo simulation. As seen in Fig. 4, the single-gaussian fit plus background is still acceptable according to the  $\chi^2/\text{ndf}$  test. However, in the low-mass region,  $M < 1550$  MeV, this fit had a poor quality. For the background fit only, the  $\chi^2/\text{point} = 2.2$ , while the overall  $\chi^2/\text{ndf}$ , which is dominated by the high-mass region, is reasonable (see Table 1).

It is interesting that the  $K_S^0 \bar{p}$  data has a peak near 1470 MeV, while the  $K_S^0 p$  channel does not have a clear peak at this mass. Generally, one could conclude that the data may contain a contribution from the unestablished  $\Sigma(1480)$  state. This conclusion is mainly supported by the comparison of the data with the Monte Carlo simulation. The parameters and the significance of this state are difficult to estimate due to the steeply falling background.

An ensemble of Monte Carlo experiments was generated in which the background shape was parameterised by the threshold function, and the background rate was simulated as the mean of a Poisson distribution in each mass bin. The probability of a similar signal anywhere in the range 1500–1560 MeV arising from statistical fluctuation of the background was below  $6 \times 10^{-5}$ . For a more realistic case, when the background was parameterised by the threshold function plus the 1465 MeV Gaussian as the starting distribution, the probability was found to be about a factor of ten lower.

The mass spectrum was studied over a large  $Q^2$  range. The signal was well seen for  $Q^2 > 60 \text{ GeV}^2$ , but, in this case, the statistics is smaller. No significant signal was found at very low  $Q^2$  ( $Q^2 = 1 - 5 \text{ GeV}^2$ ) due to a complicated background and possible acceptance effects. However, the same signal was found at  $Q^2 > 1 \text{ GeV}^2$  at low photon-proton centre-of-mass energy,  $W < 120 \text{ GeV}$ . For this  $W$  range, the charged multiplicity (and, hence,

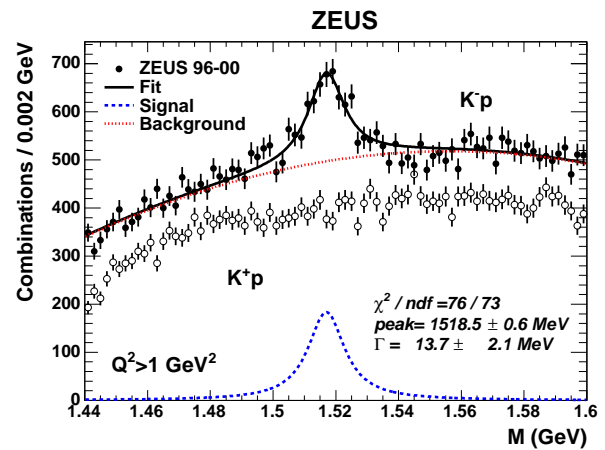


FIG. 5: Invariant-mass spectra for the  $K^+ p$  and  $K^- p$  channels (plus charge conjugates) for  $Q^2 > 1 \text{ GeV}^2$ .

the combinatorial background) is lower.

In conclusion, the results constitute evidence for the existence a narrow baryonic resonance decaying to the  $K_S^0 p(\bar{p})$  channel with the mass near 1522 MeV. This is the first observation of such resonance in high-energy colliding experiments in the phase-space regions dominated by fragmentation.

The measured mass and the width of the observed state are close to those observed in the  $K^+ n$  channel [16], and agree well with the theoretical expectations [5]. The PDG reports no any  $\Sigma$  state in the invariant-mass region 1480–1560 MeV, and no peak with a similar mass was observed in  $\Lambda\pi$  decays. This favours the conclusion that the observed peak can be interpreted as a pentaquark candidate. In this interpretation, the signal seen in the  $K_S^0 \bar{p}$  channel corresponds to an antipentaquark with a quark content of  $\bar{u}\bar{u}d\bar{d}s$ .

### III. $\Theta^{++}$ STATE?

If  $\Theta^+$  is an isotensor state, a  $\Theta^{++}$  signal can be expected in the  $K^+ p$  spectrum [15]. The  $K^\pm p(K^\pm \bar{p})$  invariant mass spectra were investigated in a wide range of minimum  $Q^2$  values, identifying proton and charged kaon candidates using the  $dE/dx$  information. The proton candidates inside the  $dE/dx$  proton band were required to have  $dE/dx > 1.8$  mips, while the kaon candidates were reconstructed in the kaon band after the restriction  $dE/dx > 1.2$  mips. For  $Q^2 > 1 \text{ GeV}^2$ , no peak was observed near 1522 MeV in the  $K^+ p$  and  $K^- \bar{p}$  spectra, while a clean signal was seen in the  $K^- p(K^+ \bar{p})$  channel at  $1518.5 \pm 0.6(\text{stat.}) \text{ MeV}$ , corresponding to the PDG  $\Lambda(1520)D_{03}$  state, Fig. 5.

The numbers of the reconstructed  $\Lambda(1520)$  and  $\bar{\Lambda}(1520)$  candidates agree very well with each other. The same good agreement was found for  $K^+$  and  $K^-$ , as well as for  $p$  and  $\bar{p}$  candidates. This indicates negligible contri-

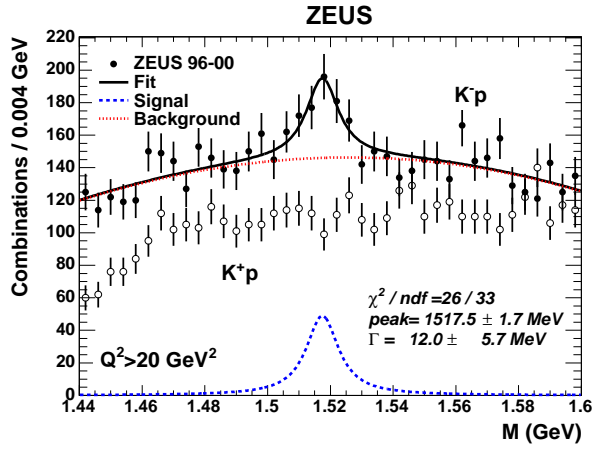


FIG. 6: Invariant-mass spectra for the  $K^+p$  and  $K^-p$  channels for  $Q^2 > 20 \text{ GeV}^2$ .

butions from the proton remnant, as well as from possible secondary-scattering events.

The  $K^+p$  and  $K^-p$  mass spectra were investigated at  $Q^2 > 20 \text{ GeV}^2$ , i.e. in the kinematic region where the 1522 MeV peak is clearly pronounced for the  $K_S^0 p (\bar{p})$  channel. Fig. 6 shows the mass spectra for  $Q^2 > 20 \text{ GeV}^2$ . Again, no sign of a peak was found in the  $K^+p$  decays.

The failure to observe  $\Theta^{++}$  indicates that the  $\Theta^+$  state is not isovector or isotensor.

In contrast to the  $K_S^0 p (\bar{p})$  state, the detector acceptance for  $\Lambda(1520)$  baryons decreases faster with increase of  $Q^2$ , since the momenta of  $K^\pm$ -mesons were restricted by the requirement  $dE/dx > 1.2 \text{ mips}$  (i.e. high-momentum mesons were not used in the reconstruction), while  $K_S^0$  used in the  $K_S^0 p (\bar{p})$  reconstruction were not restricted in the total momenta. Since the detector acceptances are significantly different for the  $K_S^0 p (\bar{p})$  and  $K^-p$  measurements, direct comparisons of the production rates of possible pentaquarks and  $\Lambda(1520)$  state are not possible before taking into account the detector acceptance effects.

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